

Possibilities of electricity generation in the Republic of Croatia by means of low temperature geothermal sources

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ABSTRACT

In the Republic of Croatia there are several medium temperature geothermal sources with relatively low temperature of geothermal water in the range 90–125 °C, by means of which it is possible to produce electricity. For the generation of electricity from medium temperature geothermal sources, binary plants come to the fore, either with the Organic Rankine Cycle (ORC) or with the Kalina cycle. In literature, the Kalina cycle is cited as thermodynamically more favorable than ORC, i.e. reaching higher thermal efficiency and giving more power. On the other hand, experiences of the authors of this paper published in previous papers, obtained on the basis of calculations for a medium temperature geothermal source in the Republic of Croatia with higher temperature of geothermal water in the range 140–175 °C (Velika Ciglena - 175 °C and Lunjkovec–Kutnjak – 140 °C) are opposite - the ORC cycle is thermodynamically better than the Kalina cycle! Now, in this paper the comparison of the ORC and Kalina cycles is performed on the basis of energy analysis results for a medium geothermal field with relatively low temperature of geothermal fluid: Babina Greda (125 °C). Also in this case, ORC has better the thermal efficiency (the First Law efficiency): 11.53% vs. 10.65%. Again, this is explained by relatively high average annual temperature of cooling air in condenser (15 °C) that has more unfavorable influence in the Kalina cycle than in the ORC. The ORC gives net power of 2509.9 kW with mass flow rate 47.77 kg/s, while the Kalina cycle gives net power of 2317.37 kW with mass flow rate 19.81 kg/s.

1 Introduction

In recent years, accelerated consumption of fossil fuels has caused lots of serious environment problems such as global warming, ozone layer destruction, acid rains and contamination of lands and seas [1]. Furthermore, along with the fast development of industry, energy shortage and blackouts have appeared more and more frequently all over the world. Therefore, renewable energy sources like solar energy, wind energy, biomass and geothermal energy for electricity production become important [2].

The geothermal energy available from the Earth is potentially enormous. A United States Government energy agency estimates that the total energy available from global geothermal resources is approximately 15000 times the energy contained in all the known oil and gas reserves in the world [3]. Unlike solar and wind energy, the supply of geothermal energy is constant and doesn't vary with the time of day or change with the weather. Although geothermal energy may always be available when it is needed, like the other two sources it is not always available where it is needed. Generally, geothermal energy is a clean energy source as it meets

the criteria of two important concepts in energy source exploitation: renewability and sustainability.

Simply speaking, geothermal energy is the energy contained in the Earth's interior. The Earth's core maintains temperatures in excess of 6000 K due to the heat generated by the gradual radioactive decay of the elements it contains. Modern estimates for the total present rate of radioactive heat generation within the Earth are about 2×10^{13} W [3]. This heat continuously flows outwards from the hot core due to conductive and convective flows of the molten mantle beneath the crust.

Estimates of the mean heat flux through the Earth's surface resulting from its radioactive core vary between 0.04 and 0.08 W/m² [3]. At the surface the heat dissipates into the atmosphere and space. This geothermal heat flow is trivial compared with the 1000 W/m² of solar energy impinging on the surface of the Earth in the other direction from the Sun (1367 W/m² at the outer surface of the atmosphere) [3]. Never the less it is sufficient to allow harvesting of geothermal energy on a commercial basis.

The diagram presented on Figure 1 shows the Earth's temperatures resulting from its internal heat generation and heat flows.

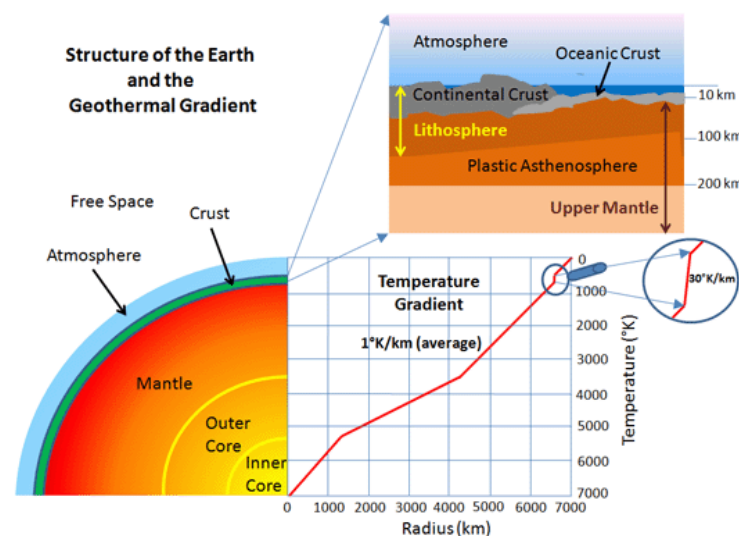


Figure 1 Structure of the Earth and the geothermal gradient [3]

The overall thermal energy capacity of the Earth is estimated at around 12.6×10^{24} MJ, of which the Earth's crust contains 5.4×10^{21} MJ, thus heat capacity of the Earth is enormous, but only a very small part can be exploited economically [4]. Geothermal energy is not inexhaustible, but the stored amounts are so large, especially taking into account the energy accumulated in hot dry rocks, that with respect to the energy demand of humanity, it can be considered as inexhaustible [4].

The increase of temperature by depth is called a geothermal (temperature) gradient, Figure 1. The geothermal or temperature gradient is the rate of increase in temperature per unit depth in the Earth due to the outflow of heat from the centre. The temperature gradient between the centre of the Earth and the outer limits of the atmosphere averages about 1 °C/km [3]. The temperature gradient in the Earth's fluid layers, the magma, tend to be lower because the mobility of the molten rock tends to even out the temperature. This mobility however does not exist in the solid crust where temperature gradient is consequently much higher, typically between 25 and 30 °C/km depending on the location and higher still in volcanic regions and along tectonic plate boundaries where seismic activity transports hot material to near the surface [3]. At depths of 10

km in the Earth's crust therefore the temperature could be as high as 300 °C which makes practical energy capture possible [3].

Local geothermal gradient is essential for geothermal energy exploitation, because it indicates the presence of hot reservoirs at reachable depth. The average value of the geothermal gradient for Europe is 0.03 °C/m [4].

Geothermal energy exploitation does not refer to the energy that reaches the surface by conduction, but the energy that is accumulated within the Earth's crust, whether in the form of hot water or steam reservoirs, or in the form of hot dry rocks. To make exploitation possible, it is necessary to take advantage of the natural circulation of water, or to create artificial conditions for such circulation. Thus the heat is brought from the reservoir to the surface by means of convection, rather than conduction. The basic principle is that water, sinking from the surface into deeper layers, is heated, and returned to the surface due to change in density.

It is estimated that more than 97% of current geothermal reservoir production is from magmatically driven reservoirs [5]. Geothermal reservoirs may also develop outside regions of recent volcanic activity, where deeply penetrating faults allow groundwater to circulate to depths of several kilometers and become heated by the geothermal gradient [6].

More than 90% of exploited fields are liquid-dominated under pre-exploitation conditions with reservoir pressures increasing with depth in response to liquid-phase density. Vapor-dominated systems, such as The Geysers in California (USA) and Larderello (Italy) have vertical pressure gradients controlled by the density of steam.

Nowadays, depending on the geothermal fluid phase, temperature, composition, etc., geothermal energy is used indirectly (e.g. by passing through turbines) or directly (by exchanging heat with another medium), i.e. for electricity generation or district heating, in greenhouses, swimming pools, for medical purposes (spa), in fish farming and in various industrial processes, thus producing savings in the use of conventional energy sources.

Presently, an international standard terminology for the classification of geothermal resources is not yet defined. The most widely used classification of geothermal sources is based on the temperature of geothermal fluid. Geothermal sources are divided into low-temperature (<100°C), medium (100 - 200°C) and high-temperature sources (> 200°C) [7].

The most important way of exploiting high-temperature geothermal resources (> 200 °C) is the production of electricity. The simplest and most cost-effective way of electricity production is from the vapor-dominated systems, in the so-called dry steam geothermal power plants: steam is cleaned and then passed directly into low-pressure turbines. Heat is converted to mechanical energy by passing steam through low-pressure steam turbines. More sophisticated methods of exploitation (such as flash power plants and binary power plants), developed for exploitation of medium-temperature, liquid-dominated geothermal sources (100 – 200 °C) become more and more economically competitive.

For the first time electricity was generated from geothermal steam at Larderello, Tuscany, Italy when Prince Piero Ginori Conti powered a 3/4-horsepower reciprocating engine to drive a small generator. By 1914, the first commercial 250 kW geothermal power plant was in continuous operation there [4].

Over the past 20–35 years, worldwide electricity production based on geothermal sources has increased significantly: the installed generating capacity has grown from 1300 MW in 1975 to almost 9730 MW in 2007 [8]. These plants produce a little more than half a percent of the world's total generated electricity, however, they play a significant role among alternative energy sources. Today, electricity is produced from geothermal energy in 24 countries worldwide, Figure 2, and geothermal energy is an important source of electricity in many countries [6].

Moreover, direct applications of geothermal heat offsetting the need for electricity production and burning of fossil fuels has also gained importance over the years; the estimated installed thermal capacity of direct-use projects was more than 28000 MW in 2005 [8]. Increase

of geothermal energy exploitation is particularly visible after the abrupt jump in oil prices in the year 1973, and due to the intensifying demands for the preservation of the environment.

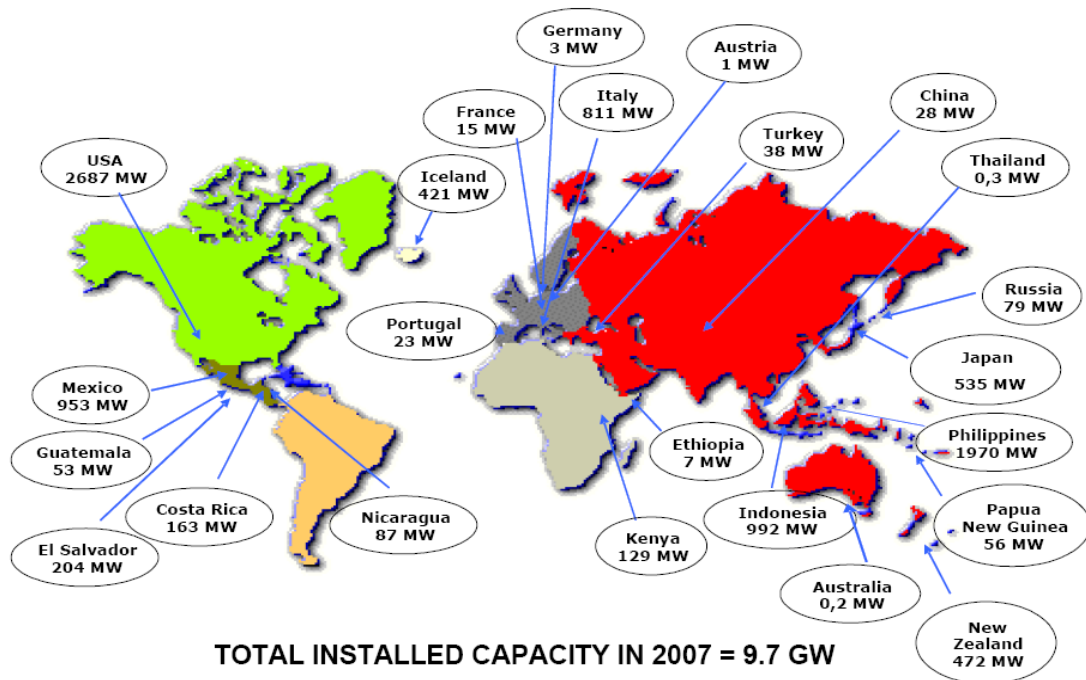


Figure 2 Installed capacity of geothermal power plants in the world in the year 2007 [6]

Among countries which increasingly use geothermal energy sources for different purposes (depending on geothermal field temperature) are the United States, Iceland (geothermal power accounts for 44% of the total energy consumption), Italy, New Zealand, France, Germany, Hungary, etc. [6].

In the Republic of Croatia there a several centuries old tradition of exploiting geothermal energy from natural sources, for medical purposes and for bathing. Besides the usage of geothermal energy in spas, techniques and technologies for obtaining geothermal energy from deep geothermal reservoirs were developed during the research of oil and gas resources.

With the development of the oil industry in the Republic of Croatia, and comparative testing of certain geothermal wells, a technological basis was created for exploiting geothermal water for recreational-medical purposes, heating, production of fruits and vegetables in greenhouses, and for the subsequent industrial thermal processing of such products (e.g. drying, pasteurization, etc.)

As early as 1998, the Energy Institute “Hrvoje Požar” prepared a Program of Geothermal Energy Usage in the Republic of Croatia, which shows that in the Republic of Croatia there are some medium temperature geothermal sources with relatively lower temperature of geothermal water in the range from 90–130 °C (e.g. Ferdinandovac - 125 °C, Babina Greda - 125 °C, Rečica - 120 °C, etc.) by means of which it is possible to produce electricity [9]. However, concrete initiatives for the construction of geothermal power plants have only recently been started.

For the production of electricity from medium temperature geothermal sources with relatively low temperature of geothermal water the binary power plants come to the fore: with ORC or Kalina cycle. The comparison of ORC and Kalina cycles will be performed on the basis of energy analysis results for the geothermal field Babina Greda (125 °C). Aim of the comparison is to propose the most suitable binary plant either with the ORC or with the Kalina cycle for medium temperature geothermal sources in the Republic of Croatia with relatively low

temperatures of geothermal water. For both cycles the optimization of main cycle parameters is performed: at ORC - the upper cycle pressure and at Kalina cycle - ammonia concentration in mixture of water and ammonia.

2 Geothermal potential of the Republic of Croatia

There is about of 28 geothermal fields, out of which 18 are in use. For the needs of space heating a total of 36.7 MW of heating power is installed with annual usage of heating energy of 189.6 TJ/year. For bathing 77.3 MW of heating power is used, i.e. 492.1 TJ/year. Until now, geothermal energy has not been used for the production of electricity [9].

In general, there are two different regions in the Republic of Croatia, both in geological and geothermal respect, Figure 3. Large differences in geothermal potential between these two basins have been discovered by investigation works with the aim of discovering oil and gas.

In the southeastern part of the country, there is the Dinarides mountain chain with predominantly Mesozoic carbonate rocks, characterized by the average geothermal temperature gradient $0.018\text{ }^{\circ}\text{C/m}$ and heat flux 29 mW/m^2 [9, 10]. In the northeast part of the country is the Pannonian basin, up to several thousands meters deep. Unlike the Dinarides basin, which has no relevant geothermal potential, in the Pannonian basin the average geothermal temperature gradient and heat flux are much greater: $0.049\text{ }^{\circ}\text{C/m}$ and 76 mW/m^2 [9, 10]. The main geothermal reservoirs are in the fractured Mesozoic and older carbonates rocks, mid Miocene carbonates, under the Pannonian basin and younger clastic sediments, with important geothermal reservoirs in their sandstone sequences [10].

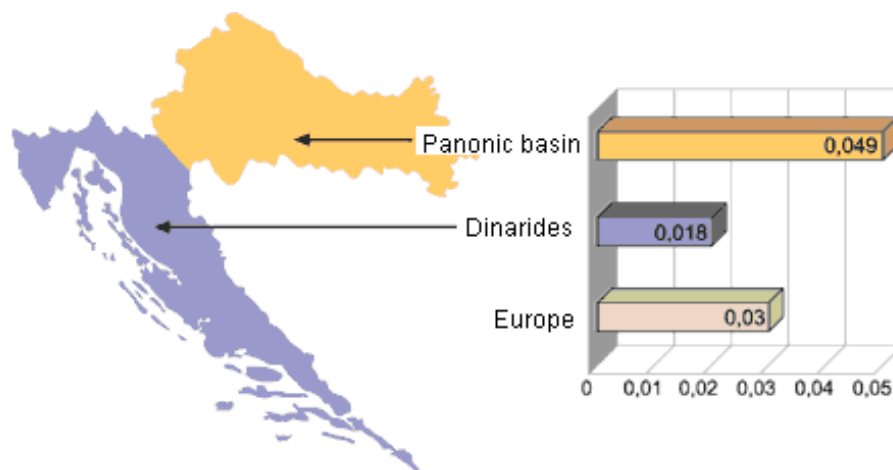


Figure 3 Average geothermal temperature gradient in the Republic of Croatia [9]

Geothermal sources in the Republic of Croatia can be divided into three groups: medium temperature sources with a temperature of $100 - 200\text{ }^{\circ}\text{C}$; low temperature sources with $65 - 100\text{ }^{\circ}\text{C}$, and geothermal sources with water temperature below $65\text{ }^{\circ}\text{C}$, Figure 4 [9]. Since the geothermal gradient in the Pannonian basin is considerably greater than the European average value, besides the already discovered geothermal fields, the discovery of new fields is to be expected in this region.

It is estimated that the entire geothermal heat potential from already developed wells in Croatia is 203.47 MW (up to $50\text{ }^{\circ}\text{C}$) i.e. 319.21 MW (up to $25\text{ }^{\circ}\text{C}$), and with complete development of the fields it would be 839.14 MW (up to $50\text{ }^{\circ}\text{C}$) i.e. 1169.97 MW (up to $25\text{ }^{\circ}\text{C}$) [9].



Figure 4 Geothermal sources in the Republic of Croatia [9]

3 Types of geothermal power plants

The production of mechanical power (i.e. electricity) from geothermal energy requires steam to drive steam turbines. Steam can be found as wet or dry steam from natural sources, or obtained by flashing the geothermal fluid. If no natural sources of steam can be found, steam can also be produced artificially in hot dry rocks (so-called advanced geothermal systems). At lower temperature levels, steam for turbine operation can be produced by the heat from geothermal fluid, evaporating a fluid with a lower boiling point than water. Such cycles are known as Organic Rankine Cycles (ORC) because originally organic substances as toluene (C_7H_8), pentane (C_5H_{12}), propane (C_3H_8) and other hydrocarbons were used as the working medium [11]. A more recent cycle in test use is the so-called Kalina cycle, which uses a mixture of water and ammonia (NH_3) as the working fluid [11].

As can be seen from the above, geothermal power plants presently in operation can be divided into three basic types: plants with dry steam, flash plants (single and double), and binary plants. Which type of plant will be installed depends on the type of source. Figure 5 shows the ranges of application of basic geothermal power plant types, depending on unit power and geothermal fluid temperature [11].

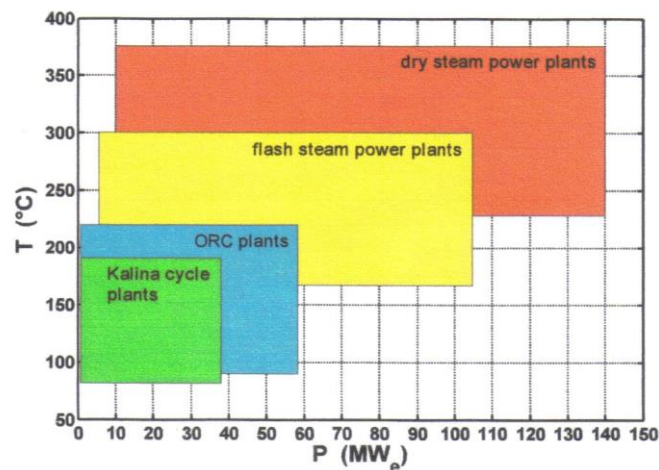


Figure 5 Application ranges of basic geothermal power plant types [11]

Dry steam dominant geothermal sources produce dry steam with a minimal amount of water. Such steam has used directly in the turbine of the geothermal power plant, where it expands, producing useful mechanical power and driving an electric generator, Figure 6 [11]. After completing expansion, the steam condenses in a condenser. A portion of the condensate can be used in the plants cooling towers, while the majority has pumped back into the underground reservoir for replenishment and maintaining of reservoir pressure.

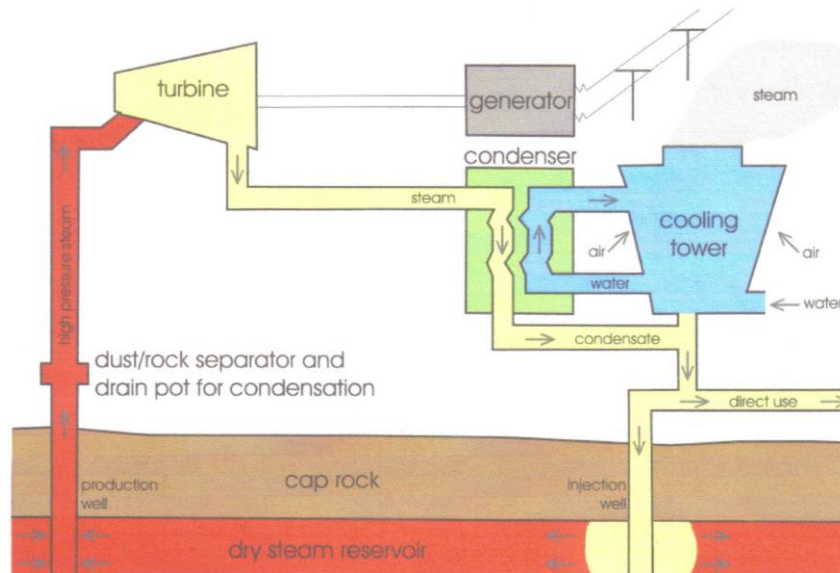


Figure 6 Geothermal power plant with dry steam [11]

For electricity production from hot water dominant geothermal reservoirs, single or double-flash power plants have used. Hot geothermal fluid evaporates in one or two evaporators (at one or two pressure levels respectively) and the produced steam expands in one or two turbines. Upon performed expansion the steam condenses and pumps back into the reservoir, as in dry steam power plants. Figure 7 shows a double-flash geothermal power plant [11].

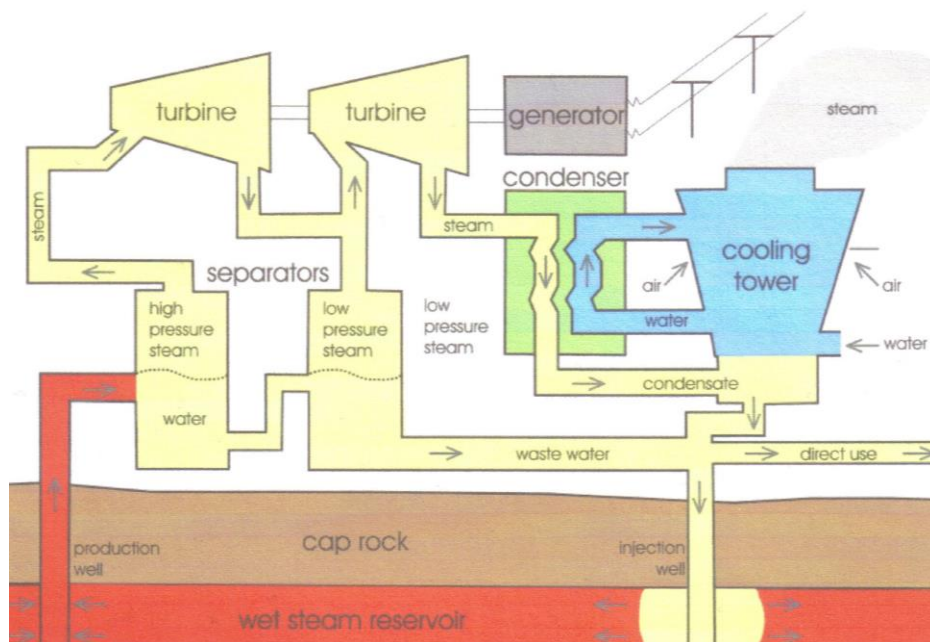


Figure 7 Double flash geothermal power plant [11]

Medium and low temperature geothermal reservoirs, with temperatures between 85 and 150 °C, produce fluids that are not hot enough for evaporating. However, these sources can be used for power generation in a binary geothermal plant with an ORC, as shown in Figure 8 [11]. In binary plants, geothermal fluid passes through a heat exchanger, where its heat has transferred to a secondary fluid with a low boiling point. The secondary fluid evaporates and the produced steam expands in the turbine producing electricity. After the expansion steam is taken to the condenser, and the condensate is fed through circulating pumps to return to the heat exchanger. Unlike in geothermal power plants with dry steam and flash plants, in binary plants the geothermal fluid does not come in contact with the turbine or other elements of the plant, apart from the heat exchanger. This relatively new technology has made possible the exploitation of numerous geothermal resources with lower fluid parameters and mass flow, by using binary systems of smaller capacity and selecting favourable working fluids. A further advantage of a large number of small units is that the cascade operating mode facilitates optimal use of resources according to current energy demand. Binary plants with the Kalina cycle should improve the thermal efficiency of energy conversion, using a mixture of water and ammonia (NH₃), which changes temperature while evaporating, unlike pure fluids that evaporate at constant temperature. So, heat transfer between the geothermal fluid and the working fluid occurs with a smaller temperature difference between the streams [12].

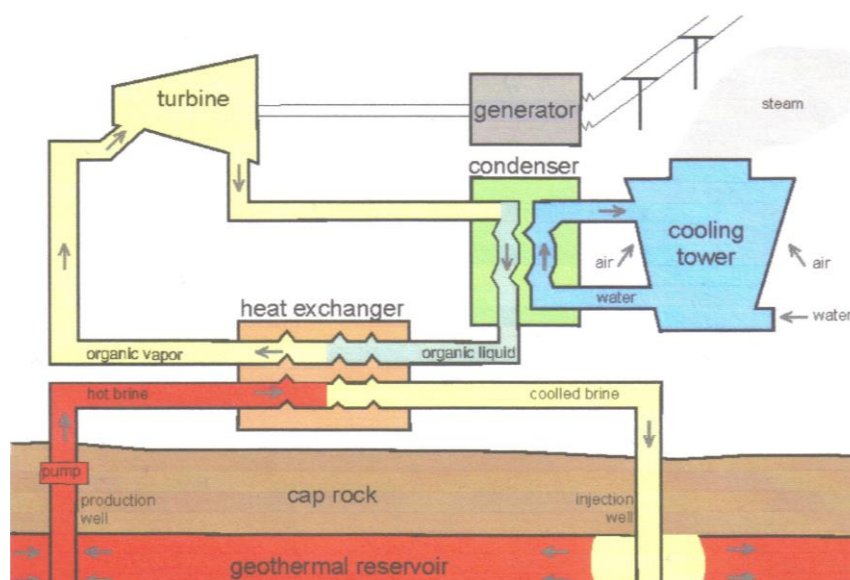


Figure 8 Geothermal power plant with binary cycle [11]

4 Case study of geothermal power plant Babina Greda

The geothermal field Babina Greda is situated in Vukovarsko-Srijemska County, in the municipality-village Babina Greda, near the town Županja. Reservoir depth is 2010 m and average thickness is 120 m. The reservoir, according to the categorization of geothermal resources, belongs to the medium temperature category [9].

The geothermal reservoir is a closed hydro-geological entirety without natural replenishment, so it is foreseen during exploitation to inject exhausted geothermal fluid back into the reservoir to ensure sustainability of the geothermal system. The temperature at the mouth of the production well is 125 °C and flow by natural outflow is 100 l/s. Geothermal water contains 5 g/l dissolved minerals [9]. More about characteristics of the geothermal field Babina Greda and the production well (BaG-1) - in the literature [13].

The majority of heat from the geothermal fluid will be used for electricity production, starting at the highest temperature level of the source (125°C). After usage in the power plant, the cooled geothermal fluid still has sufficient heat energy (70°C) for use in other processes (direct use): a system of heat distribution to a nearby fruit and vegetable drying plant, a spa (outdoor swimming pool and a hotel with a pool), greenhouses (flowers and vegetables), fish farming, etc. Artistic impression of the future geothermal power plant Babina Greda, spa and greenhouses is shown in Figure 9 [14].



Figure 9 Artistic impression of the future geothermal power plant Babina Greda and accompanying spa and greenhouses [14]

On a geothermal field with maximal fluid temperature of 125°C , the production of electricity requires the application of a binary power plant [4, 7, 15]. Therefore, the proposed technology for electricity production at the site Babina Greda is a binary plant with the ORC or the Kalina cycle. Therefore, these two technologies will be compared using results of thermodynamic calculations, i.e. of energy analysis (on the basis of The First Law efficiency). Thermodynamic calculations are performed on a computer in [16] by means of the model of binary cycle with ORC and Kalina cycle, presented in [17, 18, 19], where thermodynamic properties of working fluids are determined by REFPROP program [20].

For both cycles the optimization of main cycle parameters is performed: for ORC - the upper cycle pressure and for Kalina cycle - concentration of ammonia [16]. The presumed turbine isentropic efficiencies are 0.85 for the ORC (dry turbine) and 0.80 for the Kalina cycle (wet turbine). In both cases the presumed efficiencies for feed pumps are 0.8. In both cases, the air-cooled condensers are used, whose thermodynamic calculations have been performed with the average annual air temperature of 15°C . Air cooling is the only feasible method at the location Babina Greda because the amounts of cooling water for the water-cooled condenser are not sufficient. In thermodynamic calculations special attention is given to the values of pinch points which are not below 5°C .

4.1 ORC

A binary power plant with an ORC consists from preheater, evaporator, steam turbine with generator, feed pump and air-cooled condenser with fans as it is presented on the power plant scheme in Figure 10. The working fluid parameters (states) in characteristic points of the cycle obtained by thermodynamic calculation and presented in Figure 10 are for the design operating regime [16].

ORC CYCLE

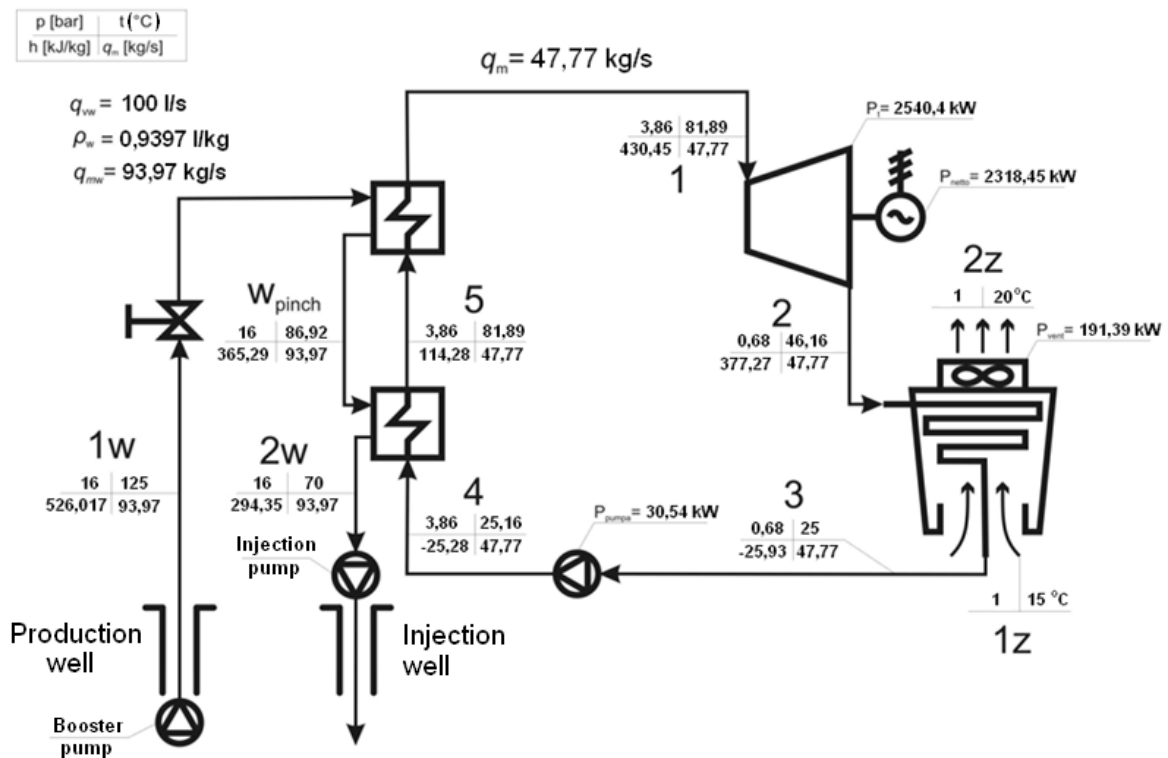


Figure 10 Scheme of geothermal power plant Babina Greda with the ORC [16]

Geothermal fluid (state 1w, 2w) transfers its heat to the working fluid - isopentane - inside the preheater and evaporator. In the preheater, condensed isopentane (state 4) has heated up to the boiling point (state 5), and transforms to dry saturated steam (state 1) within the evaporator. Dry saturated steam expands in the turbine (from state 1 to state 2) providing mechanical work to drive the electric generator. After expansion in the steam turbine, the steam is taken to the air cooled condenser. The condensation heat has transferred to the environment by forced convection of air (state 1z, 2z). The condensate (state 3) is brought to the initial pressure (state 4) by the feed pump, and returns to the preheater and evaporator. h - s diagram of ORC is presented in Figure 11 [16].

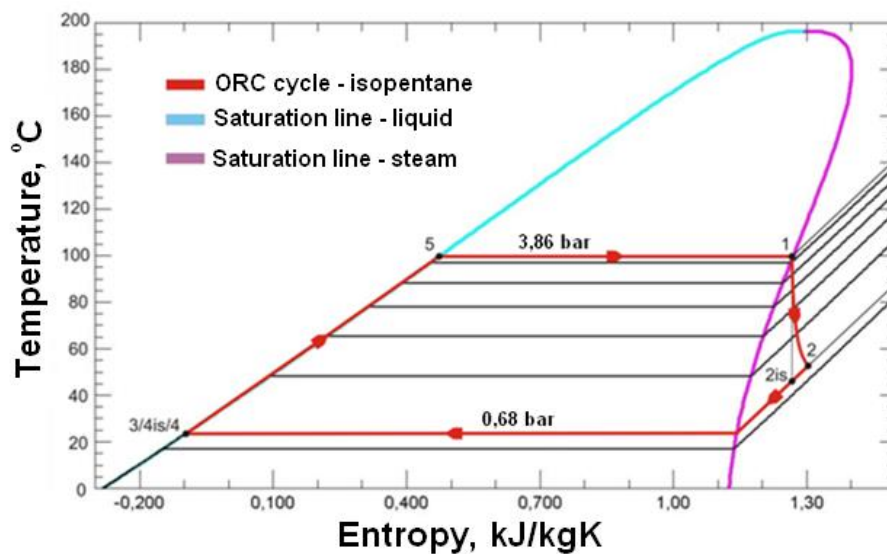


Figure 11 h - s diagram of ORC with isopentane from Figure 10 [16]

Due to the specific properties of isopentane, visible from the saturation line for vapor in the h - s diagram, Figure 11 [16], expansion in the turbine takes place in the superheated region (states 1-2). Therefore problems related to the flow of wet steam through a turbine are excluded. Thus preventing erosion of turbine blades, droplets separation, condensate draining and similar is not necessary, which simplifies the turbine design.

4.2 Optimization of the ORC

Once set up, the mathematical model of the ORC allows optimization of the cycle by changing its main parameter - the upper cycle pressure (of evaporation).

In a model with a fixed output temperature of the geothermal fluid (for secondary consumers), the heat exchanged in the preheater/evaporator is constant. By changing the upper cycle pressure the temperature of isopentane evaporation also changes, determining the mass flow of isopentane which can be evaporated by the exchanged heat, Figure 12 [16]. At lower pressure, the evaporation process starts earlier, evaporating a larger mass of isopentane with the same amount of heat, but the temperature as well as the pressure of the obtained steam is lower.

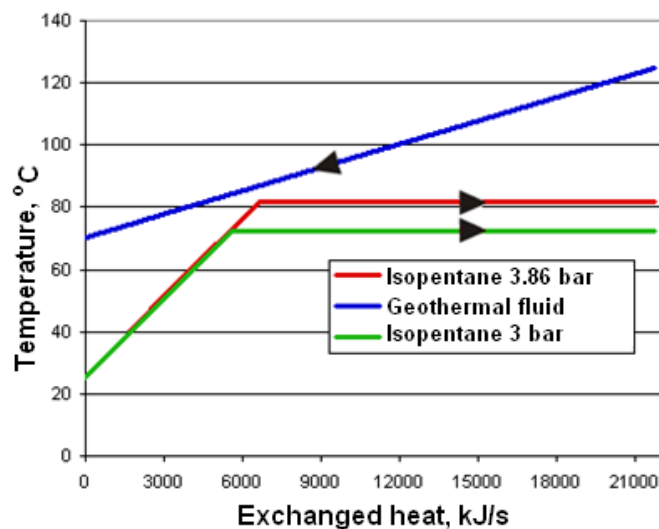


Figure 12 Comparison of isopentane vaporization at pressures 3 and 3.86 bar [16]

From the comparison shown in Figure 13 [16], it can be seen that more power is generated by steam with higher parameters, regardless the corresponding lower mass flow. Pressure increase thus leads to an increase in output power. The limit to pressure increase is represented by the minimal temperature difference between geothermal fluid and isopentane in the heat exchanger's pinch point. Optimum pressure is considered as the maximum pressure at which the pinch-point difference reaches an agreed minimum of 5°C. Cycles with upper pressure above 3.86 bar are therefore not feasible, regarding before mentioned assumptions.

The power required for feed pumps increases with the increase of cycle upper pressure, while the needed cooling fan power decreases, but their mutual effect on the total output power of the plant is approximately constant, as can be seen from the parallel lines of gross power (turbine power) and net output power, Figure 13 [16].

In case there are no secondary heat consumers at a certain location, and the aim would be to produce the maximum of electricity from the geothermal fluid, a small adaptation of the mathematical model would be necessary. The output temperature of the geothermal fluid would be taken as a variable and the order of equations would be modified. Also, in that case the optimal upper cycle pressure would not necessarily be the maximum possible pressure.

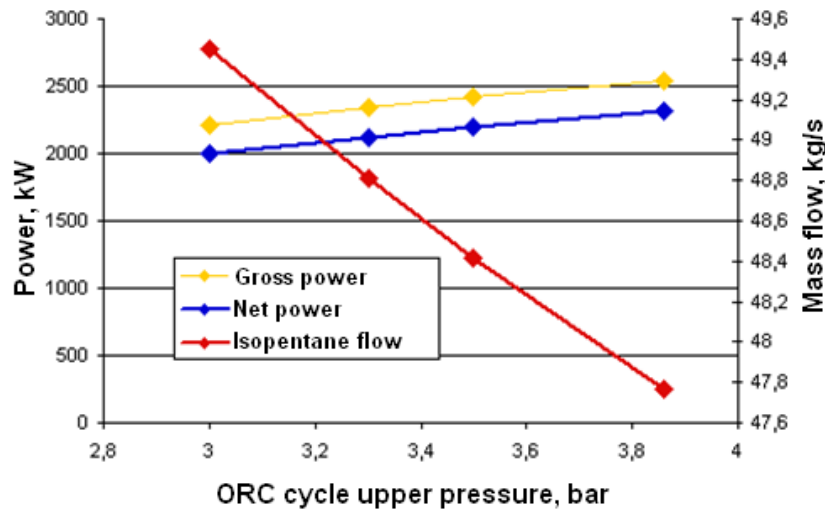


Figure 13 Comparison of ORC with upper cycle pressures of 3, 3.3 and 3.86 bar (optimum) [16]

The mathematical model of a cycle with fixed output temperature of the geothermal fluid also allows an analysis of plant operation depending on a variable temperature of ambient air. The plant is optimized to operate at an average annual air temperature of 15 °C, but operation of the plant at temperatures of 10, 20 and 25 °C was also considered, along with possible adaption of cycle parameters [16].

Ambient air temperature determines the condensation pressure of isopentane, where lower temperature is, naturally, more favorable. For example, an increase in power output of the plant from design 2320 kW to 2560 kW occurs with the decrease of ambient air temperature to 10 °C, without any adaption of the cycle. In unfavorable cases, when the air temperature is above average, a significant decrease in power output occurs. The process may then be stabilized by reducing the upper pressure, i.e. optimized to the new air temperature, as it shown in Figure 14 [16]. In addition, it is possible to increase the upper cycle pressure at an ambient temperature below average, obtaining additional power. In Figure 14 [16], optimized ORCs are shown for various ambient air temperatures. For ambient air temperature of 10 °C, the case without pressure adaption is also presented (i.e. pressure of 3.86 bar, the same as for temperature of air 15 °C).

Adaption of upper cycle pressure can be simply realised, and could be automatically regulated, which would reduce the power plant's dependence on ambient conditions.

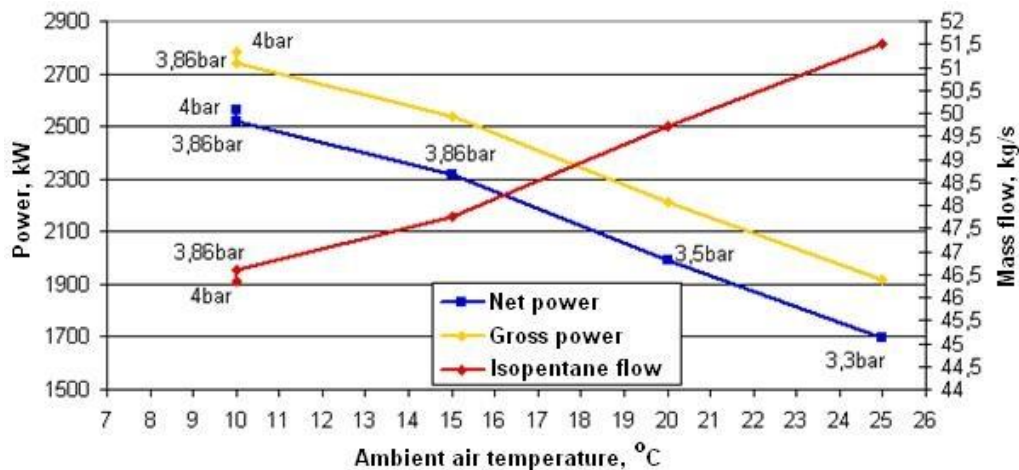


Figure 14 ORC for ambient air temperatures of 10, 15, 20 and 25 °C [16]

4.3 Kalina cycle

A binary plant using the Kalina cycle consists of an evaporator, vapor/liquid separator, a turbine with generator, a throttle valve, a mixer, air cooled condenser, low and high temperature recuperators and feed pump. The operating medium is a variable concentration mixture of ammonia and water. On the plant scheme, Figure 15, components of the plant as well as fluid parameters (states) in characteristic points of the cycle obtained by thermodynamic calculation for the design operating regime are presented [16].

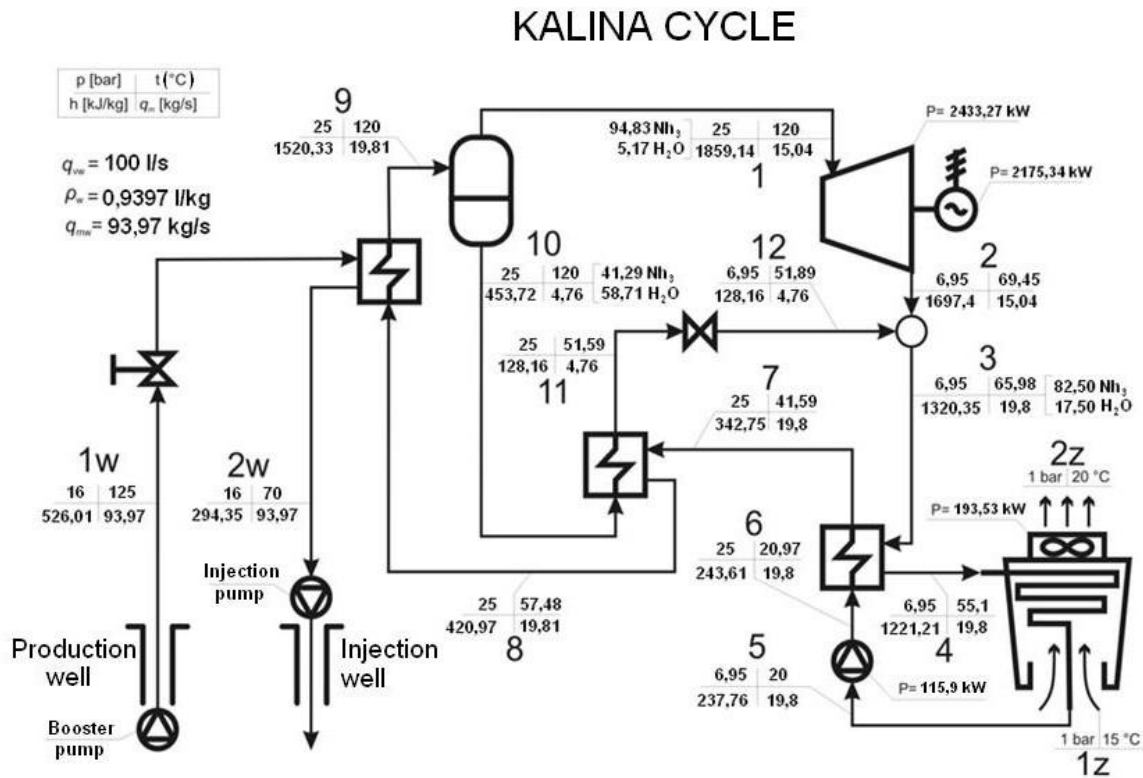


Figure 15 Scheme of geothermal power plant Babina Greda with the Kalina cycle [16]

Geothermal fluid (state 1w, 2w) transfers heat in the evaporator for evaporation of the basic water-ammonia mixture (primary concentration, state 8) to the state of wet steam (state 9). Due to different evaporation temperatures of ammonia and water, wet steam consists of an steam portion with increased ammonia concentration, and a liquid portion with reduced ammonia concentration. In the separator, the steam has extracted, and the generated dry saturated steam with increased ammonia concentration (state 1) has supplied to the turbine. In the turbine, the steam expands (from state 1 to state 2) performing useful mechanical work used to drive the electric generator. The boiling liquid with reduced ammonia concentration (state 10) separated in the separator flows through the high temperature preheater, where part of its heat has used to preheat the basic ammonia-water mixture condensate. After passing the high temperature recuperator, the liquid (state 11) passes through the throttle valve, where its pressure is reduced to the pressure of the turbine exhaust (state 12). The liquid is then introduced to the mixer along with wet steam from the turbine exhaust, forming wet steam of basic ammonia concentration (state 3). Before entering the air-cooled condensers, the wet steam passes through the low temperature preheater, where a part of its heat has transferd to the condensate returning from the condensers. At condenser entrance (state 4) the wet steam is therefore carrying less heat, so the

heat that must be rejected by the air stream (state 1z, 2z) during condensation is reduced. The condensate (state 5) passes through the feed pumps, where its pressure rises to the initial value (state 6) and then enters in the low temperature preheater where it receives heat from the flow coming from the mixer. The condensate then passes through the high temperature preheater (state 7 to state 8), receiving heat from the liquid coming from the separator. The condensate is finally introduced to the evaporator (state 8). Figure 16 presents the process of heat transfer in evaporator [16] while Figure 17 presents h - s diagram of the Kalina cycle from Figure 15.

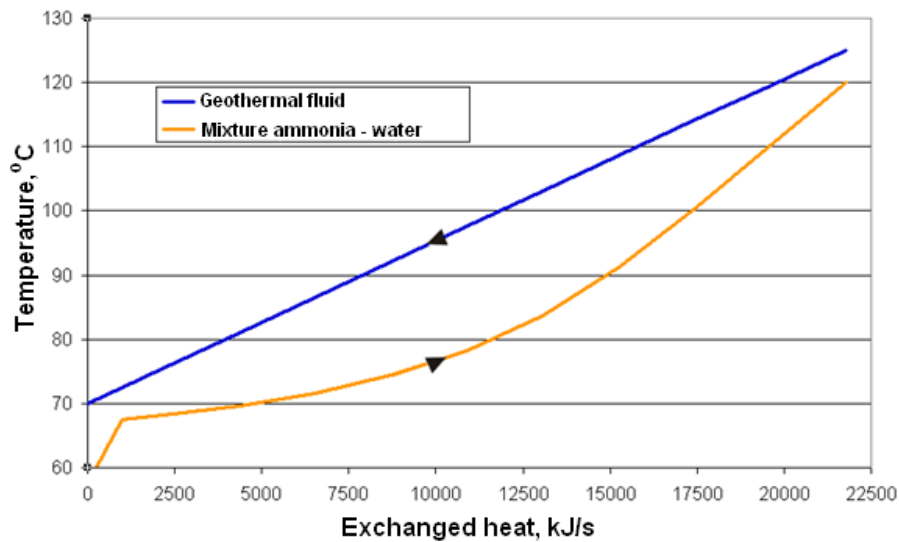


Figure 16 The process of heat transfer in evaporator [16]

In Figure 17 [16] changes in state between the separator (9) and mixer (3) are shown as dotted lines because the corresponding mixtures have a different composition, and thus different lines of saturation and constant pressure, so they would have to be shown in a different diagram.

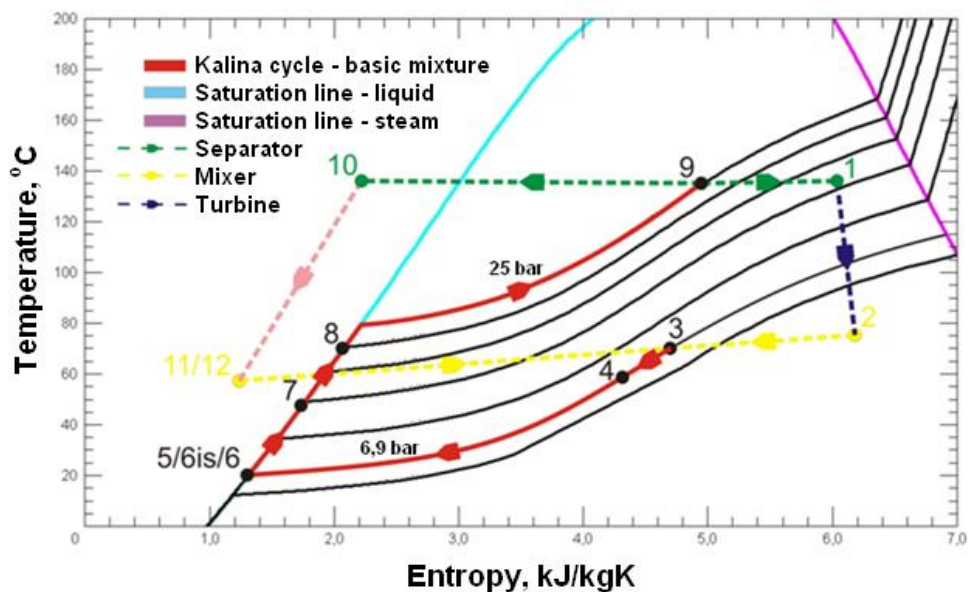


Figure 17 h - s diagram of the Kalina cycle from Figure 15, with saturation lines and constant pressure lines for the basic mixture of 82.5% ammonia [16]

The dry saturated ammonia-rich steam entering the turbine expands completely in the region of wet steam, so phenomena related to wet steam occur in the turbine, such as blade erosion, the need for separation and drainage of condensate, a reduction in turbine efficiency, etc.

4.4 Optimization of Kalina cycle

Comparing the results of the Kalina cycle obtained for different concentrations of ammonia in the basic mixture, Figure 18 [16], optimum weight fraction of ammonia in the primary mixture is 82.5%, which is also the lowest feasible concentration for the chosen pressure of 25 bar.

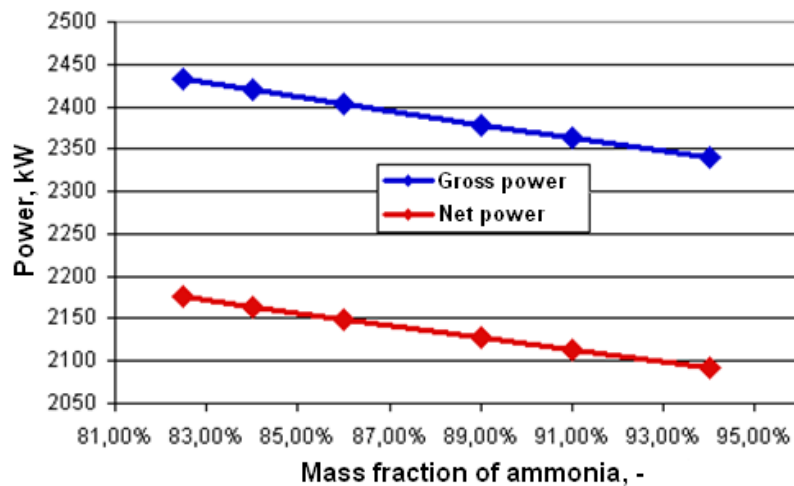


Figure 18 Power of the Kalina cycle depending on the concentration of NH_3 [16]

Figure 19 [16] clarifies this, showing that, with respect to the given model assumptions (steam parameters at the turbine entrance are equal for all cases), the mass flow of steam slowly decreases when the concentration of ammonia is lower. But the concentration decrease has significant influence on the condensation pressure, and thus on steam expansion in the turbine and the power output.

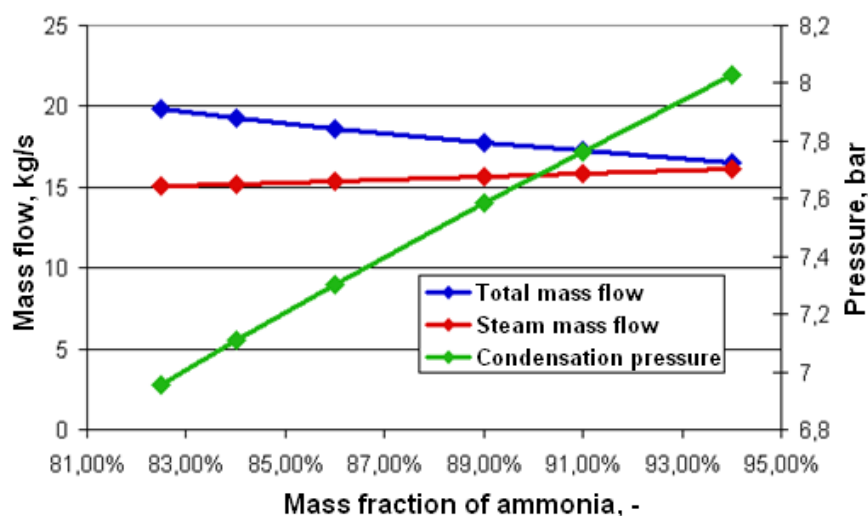


Figure 19 Mass flow and condensation pressure in the Kalina cycle in dependence on NH_3 concentration [16]

The water serves primarily as a moderator for evaporation and condensation of ammonia, modifying the vaporization line of the mixture and bringing it closer to the cooling line of the geothermal fluid.

Lower ammonia concentration in the mixture has achieved by higher quantities of water, so the total mass flow in the cycle increases. Regardless larger amounts of water heated in the evaporator (greater total flow and a greater share of water), roughly the same amount of ammonia is evaporated. Most of the water amount stays liquid and it has removed in the separator, bypassing the turbine. Also, most of the energy used to heat the water is regenerated, i.e. it remains in the cycle due to the two preheaters. Therefore, increased water mass flow produces only limited negative effects. On the other hand, increased water mass flow changes the mixture concentration, lowering its condensation pressure and thus enabling the approximately constant flow of ammonia to produce more power in the turbine.

5 Discussion and conclusions

Thermodynamic calculation of the ORC gives gross power of 2540.4 kW with mass flow rate 47.77 kg/s, while thermodynamic calculation of the Kalina Cycle gives gross power of 2433.27 kW with mass flow rate 19.81 kg/s. If from gross powers the related powers for operation of feed pumps are subtracted, which in case of the ORC is 30.54 kW and in case of the Kalina cycle 115.9 kW, net power is obtained, which in case of the ORC is 2509.9 kW and in case of the Kalina cycle 2317.37 kW. Thermal efficiency (the First Law efficiency) calculated on the basis of the obtained net power and transferred heat from geothermal fluid (21770 kJ/s) in case of the ORC is 11.53%, and in case of the Kalina cycle 10.65%.

Nor even in this case of medium temperature geothermal sources with relatively low temperature of geothermal water, Kalina cycle is not thermodynamically better from the ORC!

However, it is necessary point out that in case of medium temperature geothermal source, as the temperature of geothermal water is lower, the difference in thermal efficiencies between ORC and Kalina cycle is less. This confirm the calculations performed in [17, 18, 19]: Velika Ciglena (175⁰C) - 14.1% vs. 10.6%, Lunjkovec Kutnjak (140 ⁰C) – 13.5% vs. 12.5% and now Babina Greda (125 ⁰C) – 11.53% vs. 10.65%.

Again, in this case of geothermal power plant Babina Greda, relatively high temperature of cooling air in condenser (15 ⁰C) has more unfavourable influence in the Kalina cycle than in the ORC, so the ORC is thermodynamically better from Kalina cycle. In such conditions condensation pressure at the Kalina cycle is considerably higher than at the ORC (6.95 bar vs. 0.68 bar).

Also it is necessary take into consideration that at present, however, there is just one geothermal Kalina cycle power plant in operation in Husavik, Iceland; several more are under construction [21]. While there are reports [21] about problems during the start-up and commissioning of the only plant with the Kalina cycle in the world, at the same time the ORC has a series of advantages [22]. Today the ORC is a mature technology with hundreds of megawatts of various kinds of plants installed throughout the world [23].

Taking into account that on locations of geothermal sources in the Republic of Croatia the air cooling is the only feasible method when in all cases ORC is thermodynamically better from the Kalina cycle, and the problems that all the new technologies encounter in their early phase of application, the application of binary plants using ORC cycle is proposed for all medium temperature geothermal sources in the Republic of Croatia.

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